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Lightweight Digital Shadow Concept for Batch Size One Products and Modular Shopfloors

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***Abstract*—The Digital Twin is seen as the step towards digitalization in many areas, including the area of manufacturing which is the focus of this paper. However, the frequently application-oriented development of concepts and initial implementations make it difficult to adapt them to other applications. Especially when production deviates from the usual highly automated processes and requires high flexibility, e.g. to allow batch size one. In such a case, the Digital Twin must support modular shopfloors with flexible areas in which different production times and various tools and machines are used. It should also be possible to react promptly to problems in production. Design errors that only become apparent during production must be reported directly. In order to deal with this problem, the paper presents a concept for an abstract representation of a Digital Shadow (DS). The DS combines the disciplines of production planning and control, product life-cycle and layout planning which creates new links and enables further application scenarios. Based on this Digital Shadow, different applications can be realized that provide user-related solutions. For this purpose, a tree structure is used that links information about the product and the production environment which in this case is variable.**

***Index Terms*—Industry 4.0, Digital Twin, Digital Shadow, Flexible Manufacturing, SME**

I. Introduction

In the course of digitalization, Digital Twins are seen in many areas as a method to achieve greater flexibility and thus higher productivity. In recent years, a number of definitions and concepts have emerged for the most diverse areas of the value chain [1]. The most addressed topic in these publications deal with production planning and control. Other disciplines in which the Digital Twin is to be integrated are layout planning and the product life-cycle [2]. From the data model's point of view, keeping this disciplines separated can cause gaps in the information flow between them. In particular, if there are common problems in the production process, such as delays, assembly design errors, non-existent production resources or unreliable supply chains, a lot of manual effort is required. To overcome these problems, a new approach is needed to close the gap between the different concepts of the individual disciplines, starting from a production with low degree of automation in which complex components are manufactured.

Previous concepts for production planning and control are based on automated production [3] and are unable to map manual processes where data availability is much less reliable. For a continuous representation of the processes, a system has to be developed allowing predictions that can be corrected by sensor data arriving later. It must also be possible to correct erroneous data at a later point in time.

In certain areas, production is modularly adapted to the respective order situation and is therefore in a state of constant change. This is a basic requirement that contradicts the common concepts in which the layout of the production is set as an unchangeable constant [4]. In this constantly changing environment, collaborating robots are to be integrated which support the worker in his work and thus require a good overall understanding of their environment. They should obtain this understanding from the Digital Twin.

Due to the different users and their needs for the Digital Twin, an encapsulation of the structured digital representation of the reality from the applications is additionally necessary. This should considerably reduce the development effort and additionally reduce data duplication caused by the many different systems currently used in production. A high degree of abstraction should be achieved and the data must be available in a form that is simplistic and easy to read by developers and machines. Thus the Digital Shadow will link and structure the islands of information that are created during the product life-cycle and thus prevent the often mentioned digital artifacts [3] and duplicates [5].

Tao et al. [5] described a Digital Model in 2018 as the center of various phases in the product life-cycle. The concept provides a separate Digital Twin for each area which tends to cause unnecessary duplication and therefore requires synchronization and increased memory usage. He also states that there is a particular need for research in the area of data acquisition and data structuring. In 2019, Bao et al. [6] presented a concept that introduces models for the Product Twin, Process Twin and Operation Twin. The tree structure was introduced as a possible representation. The Product and Process Twins (including Asset Twin) are linked via an Operation Digital Twin. The concept can be applied to many areas of product life-cycle and production planning and control, but does not include changes in the layout and provides separate twins for the different areas.

This work will present a new concept for a linked Digital Shadow. The tree structure as a representation of the Digital Twin is taken up and extended by aspects of layout planning. Expected advantages are a easier generation of more comprehensive information of the whole production process and reduction of duplicates by linking the three disciplines and the applicability in modular productions with poor data situation as in productions with low degree of automation.

II. Digital Twin/Shadow

A. Definition

The most common definition for the Digital Twin is from Glassgen and Stargel [7] from the year 2012: "the Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product and uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin." Nowadays, this definition must be extended to include the aspect of twin generation for processes. Kritzinger makes a further distinction based on the degree of integration, specifying that only a system that allows bidirectional communication between physical and digital product or process is a Digital Twin [2]. Accordingly, the new concept presented is to be classified as a Digital Shadow, since there is only an autonomous path for the data flow from the physical object to the digital one.

B. Concept

The concept should work within the general conditions presented in chapter I and additionally fulfill the following requirements:

- lightweight,
- validity against factory and product changes with capturing of serial number and configuration required,
- different views and simulation applications,
- error correction using sensor data or manual corrections,
- extends existing dataset without duplication,
- persistent through the use of databases,
- readable for humans and machines,
- implies mechanisms to allow the implementation of a security system and policies.

Figure 1 shows the structure of the new concept. The center is the tree structure which is the interface between the applications and the databases. An example is given in the evaluation chapter III.

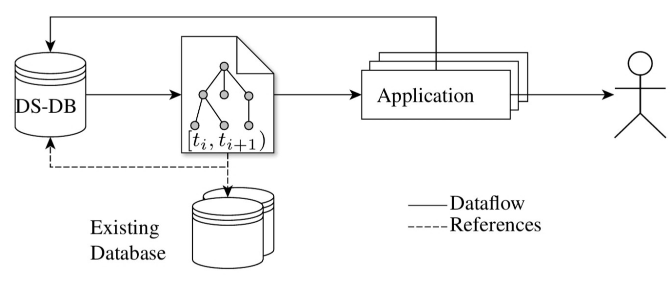


Fig. 1. Concept of the Digital Shadow, with intermediate tree structure. The tree structure is generated from the DS-DB and contains references to the various other existing databases. User-related applications access the tree structure and request their required data.

The human- and machine-readable tree structure is generated from the Digital Shadow Database (DS-DB) and represents a generic object as an attributed tree node at the time point t_i or in the time period $[t_i, t_{i+1})$. A node in this tree structure can be any object, from the atomic component of the product to the entire shopfloor. This makes it possible to combine information of the product and the modular shopfloor. Using the attributes, references to data from the DS-DB and other databases can be specified in the tree structure to achieve a comprehensive representation of the real object.

The applications can request subtrees as views of the DS for a specific point in time or period. This provides an overview of the links and available data in the DS at the beginning. Subsequently, the data required for the specific application is then requested via the references. This principle was already described in the Shneiderman Mantra [8] and offers the advantage that less data overhead is generated. In addition, the prevailing data policy in the company can be continued and data can only be made available to authorized users. Data generated in the applications can be sent directly to the corresponding databases.

C. Data model

The Digital Shadow is a function which maps the time to two dimensions: the tree structure according to the physical object structure and an attribute vector of each object. The tree structure combines the product and the shopfloor. Each real object is referenced by n typed tree nodes which are distinguished by the timestamps of updates. The tree structure is achieved by parent-child references exclusively using the part identifiers. Parent-child relational type constraints can be defined to limit the number of options. The model is extensible to accommodate major changes in manufacturing and the product by adding nodes, node types and type constraints as well as node attributes.

An example of a shopfloor tree structure can be seen in figure 2. Thus a hole factory structure including the fitting areas, machines and tools as well as the assemblies and parts can be mapped to a Digital Shadow. Physical movements and assembly activities are applied by changes in the parent/child references of the relevant nodes and its parents. A change implies an update of the node, hence a new entry in the DS database is added. Changes can be implemented by delta approaches to shrink the data usage.

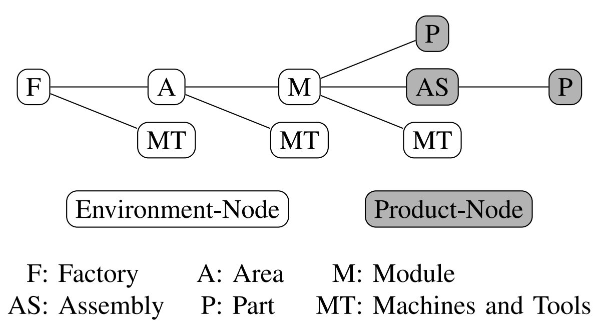


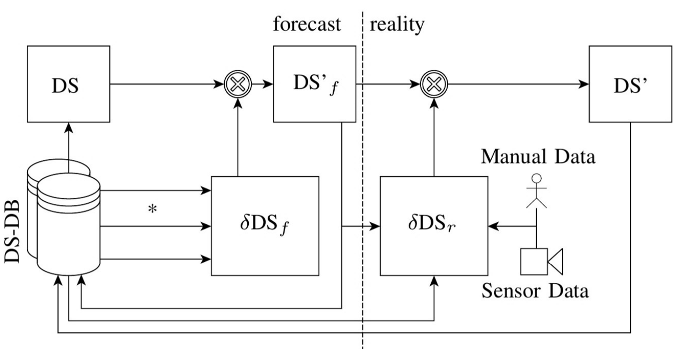
Fig. 2. Example of an hierarchical model structure for a Digital Shadow of a modular shopfloor. The typified tree structure allows the representation of the shopfloor layout and in relation to it the product and machines and tools. Process sequences are represented by the temporal change of the tree structure.

D. Calculation of an element state and error correction

The calculation of a Digital Shadow seen in figure 3 uses a network of databases and an optional error correction based on information from various sensors and manual correction procedures. Temporal changes in a DS are implemented by inducing δ information to a DS, symbolized by the $\bigotimes$ operator. A forecast can be determined by the model-based shadow DS'$_f$ with information from the databases (DS-DB and others) to calculate $\delta\mathrm{DS}_f$. Information required for this are among others: assembly instructions, CAD/3D models and process planing. A model-based shadow ignores any deviation from the real world. Optionally, the DS'$_f$ is used to calculate a real representation shadow DS') applying a real world correction $\delta\mathrm{DS}_r$ (see figure 3, right side). This correction shows the target/actual deviations which is interesting for production planing applications. The model-based shadow DS'$_f$ and real representation shadow DS' are defined as following:

$$
\begin{aligned}
\mathrm{DS'}_f &= \delta\mathrm{DS}_f \bigotimes \mathrm{DS}_{t_i} \\
\mathrm{DS'} &= \delta\mathrm{DS}_r \bigotimes \mathrm{DS'}_f \\
&= \delta\mathrm{DS}_r \bigotimes \delta\mathrm{DS}_f \bigotimes \mathrm{DS}_{t_i}
\end{aligned}
$$

To determine DS', the initial state DS_{t_0} must be defined. The initial state is the first known state of the real world object. If the whole production chain is known, the initial state equals to the empty quantity. The calculation of a DS is then performed iteratively by sequentially applying DS changes $\delta\mathrm{DS}_f$ and $\delta\mathrm{DS}_r$ to the temporal predecessor and recursively by determining the DS for each node in the assembly tree, as shown in Figure 3.



* Required data: fitting instructions, simulation data etc.

$\mathrm{DS_f}$: DS-Forecast $\mathrm{DS_r}$: DS-Real
DS-DB: Digital Shadow Database

Fig. 3. Calculation overview of the Digital Shadow. Divided into a section for predictions and a section for correcting the predictions by using data from reality.

III. Evaluation

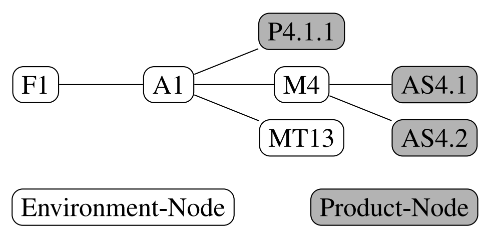
The concept was manually tested for its feasibility on several real-life examples. The procedure is explained below using fictitious data.

The example described here is a time step in the assembly of a component using a collaborating robot that confirms its working steps in the system. The data structure in the database and the resulting tree at the two points at t_0 and t_1 is shown as an example.

TABLE I
Status table at the point in time t_0. The individual elements are listed with the corresponding relationships to the other elements.

Element	Time-stamp	Tree		Attributes
		Children	Parent	
F1	t_0	A1	-	name: [..], area: [..], ...
A1	t_0	MT13 M4 P4.1.1	F1	safety level: [..], area: [..], ...
MT13	t_0	-	A1	name: [..], s/n: [..], ...
M4	t_0	AS4.1 AS4.2	A1	area: [..], processes: [..], ...
P4.1.1	t_0	-	A1	p/n: [..], count: [..], ...
AS4.1	t_0	-	M4	s/n: [..], name: [..] instruction states: [..], customizations: [..], ...
AS4.2	t_0	-	M4	||

Table I shows an extract of the Digital Shadow database at time t_0. The resulting tree is depicted in figure 4 and illustrates the connection of machines, parts and assemblies to the modular shop floor.



F: Factory A: Area M: Module
AS: Assembly P: Part MT: Machines and Tools

Fig. 4. Hierarchical model structure at point in time t_0. Shown are the relationships between the elements found in table I.

In the next time step, the robot arm carried out the task of assembling the part into the assembly and confirmed this in the system. Table II shows the corresponding changes. With the new time stamp t_1, the new dependencies were entered. For area A1 and assembly AS4.1 the children and for part P4.1.1 the parents have changed. The changes shown in table II are reflected in the human readable tree of the Digital Shadow, as shown in figure 5. Part P4.1.1 has moved from its storage location in Area A1 to the AS4.1 assembly. Compared to other solutions structural changes in the modular shopfloor would be easy to implement in the structure. Requests arriving from applications to the Digital Shadow will receive the requested extract of the tree, which will take into account the updates up to the desired time.

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TABLE II
Status table at the point in time t_1. The table I was extended by the changes made up to the point in time t_1. The entries are provided with the timestamp t_1. For a better overview, the attributes are not shown.

Element	Timestamp	Tree	
		Children	Parent
F1	t_0	A1	-
A1	t_0	MT13 M4 P4.1.1	F1
MT13	t_0	-	A1
M4	t_0	AS4.1 AS4.2	A1
P4.1.1	t_0		A1
AS4.1	t_0	-	M4
AS4.2	t_0	-	M4
A1	t_1	MT13 M4	F1
P4.1.1	t_1	-	AS4.1
AS4.1	t_1	P4.1.1	M4

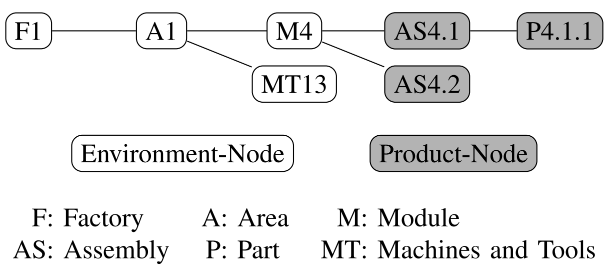

Fig. 5. Hierarchical model structure at point in time t_1. Shown are the changed relationships between the elements found in table II.

The tested use cases covered cases including changes in the structure of the workshop as well as material movements and assembly steps. In all use cases it was possible to represent the changes with the Digital Shadow.

IV. Conclusion and Future Work

The paper presents a concrete data structure for a Digital Shadow that successfully combines the aspects of production planning and control, layout planning and product life-cycle. All criteria required in chapter II were fulfilled. In the product life-cycle, the link between design and production was particularly successful. Feedback from the shopfloor via the DS directly influences the design optimization of the corresponding components. Changes made, e.g. to building instructions, are directly fed back into production. Due to its high modularity and the integration of existing data sets, the concept can also be extended to other areas of the product life-cycle. Because of the predictions and correction possibilities, the system is well suited for shopfloors with a low degree of automation, where only a few data points are available.

The integration of the human- and machine-readable tree structure as an abstracted interface for applications on the distributed datasets of a production simplifies the new development of applications. It grants new possibilities for linked data without creating too much overhead in the operation. The ability to query subtrees makes it possible to generate an application dependent extracts which are based on company policies and user permissions. Type constraints partially validate changes made in the workshop or even the product in the tree.

The next step is to develop a concept for data acquisition in a manual production with low degree of automation. For this purpose, a wide variety of sensors will be integrated and existing data sources will be included to enable non-invasive acquisition of environmental and process data. In addition, the structure of the Digital Shadow is to be extended by fields for worker movements and activities. In the last step, the possibility of controlling the production from the Digital Shadow would be conceivable in order to develop the Digital Shadow to a Digital Twin.

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